4. Psychophysical Strength

Theory and Description of the Psychophysical Methodology

According to contemporary psychophysical theory, the relationship between the strength of a perceived sensation (S) and the intensity of a physical stimulus (I) is best expressed by a power relationship.[1]

$$S = kI^n \tag{1}$$

This psychophysical principle has been applied to many practical problems, including the development of scales or guidelines for effective temperature, loudness, brightness, and ratings of perceived exertion. Based on the results of a number of experiments using a variety of scaling methods and a number of different muscle groups, the pooled estimate of the exponent for muscular effort and force is 1.7.[2]

When applying this principle to work situations, it is assumed that individuals are capable and willing to consistently identify a specified level of perceived sensation (S). For manual materials handling tasks, this specified level is usually the *maximum acceptable weight* or *maximum acceptable force.* These phrases are defined by the instructions given to the test subject:[3]

> *You are to work on an incentive basis, working as hard as you can without straining yourself, or becoming unusually tired, weakened, overheated, or out of breath.*

If the task involves *lifting,* the experiment measures the maximum acceptable weight of lift. Similarly, there are maximum acceptable weights for *lowering* and *carrying.* Such tests are isoinertial in nature; however, in contrast to the tests described in Chapter 3, they are typically used to test submaximal, repetitive handling capabilities. Data are also available for *pushing* and *pulling.* These are reported as maximum acceptable forces and include data for initial as well as sustained pulling or pushing.

Why Use Psychophysical Methods?

Snook identified several advantages and disadvantages to using psychophysical methods for determining maximum acceptable weights.[4] The advantages include:

- Realistic simulation of industrial work (face validity);
- Ability to study intermittent tasks (physiological steady state not required);
- Results are consistent with the industrial engineering concept of "a fair day's work for a fair day's pay";
- Results are reproducible; and
- Results appear to be related to low-back pain (content validity).

Disadvantages include:

- Tests are performed in a laboratory;
- It is a subjective method that relies on self-reporting by the subject;
- Results for very high frequency tasks may exceed recommendations for energy expenditure; and
- Results are insensitive to bending and twisting.

Liberty Mutual preferred to use the data derived from these studies to design a job to fit the worker since this application represented a more permanent, engineering solution to the problem of low-back pain in industry.[5] This approach not only reduces the worker's exposure to potential low-back pain risk factors, but also reduces liability associated with worker selection.[5]

Published Data

Liberty Mutual

Snook and Ciriello at the Liberty Mutual Insurance Company have published the most comprehensive tables for this type of strength assessment.[6] The most recent data are summarized in nine tables, organized as follows:[6]

1. Maximum acceptable weight of lifting for males.
2. Maximum acceptable weight of lifting for females.
3. Maximum acceptable weight of lowering for males.
4. Maximum acceptable weight of lowering for females.
5. Maximum acceptable forces of pushing for males (initial and sustained).
6. Maximum acceptable forces of pushing for females (initial and sustained).
7. Maximum acceptable forces of pulling for males (initial and sustained).
8. Maximum acceptable forces of pulling for females (initial and sustained).
9. Maximum acceptable weight of carrying (males and females).

Other Sources

Ayoub et al.[7] and Mital[8] have also published tables for maximum acceptable weights of lift. Even though their tables are similar in format and generally in agreement with those from Liberty Mutual, there are some differences. Possible sources for these differences may be differences in test protocol, differences in task variables, and differences in subject populations and their characteristics.

Experimental Procedures and Methods

For the sake of simplicity and convenience, the Liberty Mutual protocol for lifting or lowering and an excerpt from the lifting table will be used as examples for this section. The protocols used by Ayoub et al.[7] and Mital[8] were similar, but not exactly the same. The reader should refer to the original publications for details.

The Liberty Mutual experimental procedures and methods were succinctly reviewed in their most recent revision of the tables.[6] The data reported in these revised tables reflect results from 119 second-shift workers from local industry (68 males, 51 females). All were prescreened to ensure good health prior to participation. These subjects were employed by Liberty Mutual for the duration of the project (usually 10 weeks). All received 4 to 5 days of conditioning and training prior to participation in actual test sessions.

Test subjects wore standardized clothing and shoes. The experiments were performed in an environmental chamber maintained at 21°C (dry bulb) and 45% relative humidity. Forty-one anthropometric variables were recorded for each subject, including several isometric strengths and aerobic capacity.

A single test session lasted approximately 4 hours and consisted of five tasks. Each task session lasted 40 minutes, followed by 10 minutes rest. Most subjects participated in at least two test sessions per week for 10 weeks. In general, a subject's heart rate and oxygen consumption were monitored during the sessions.

Lifting or Lowering Tasks

In a lifting or lowering task session, the subject was given control of one variable, usually the weight of the box. The other task variables would be specified by the experimental protocol. These variables include:

1. *Lifting zone* — whether the lift occurs between floor level to knuckle height (low), knuckle height to shoulder height (center), or shoulder height to arm reach (high).
2. *Vertical distance of lift* — the vertical height of the lift within one of these lifting zones. The specified values for distance of lift in the tables are 25 cm. (10 in.), 51 cm. (20 in.), and 76 cm. (30 in.). It is possible to use linear extrapolation for lift distances not exactly equal to one of these values.
3. *Box width* — the dimension of the box away from the body. The three values of box width are 34 cm. (13.4 in.), 49 cm. (19.3 in.), and 75 cm. (29.5 in.). It is possible to use linear extrapolation between these values.
4. *Frequency of lift* — expressed as one lift per time interval, including intervals of 5 seconds, 9 seconds, 14 seconds, 1 minute, 2 minutes, 5 minutes, and 8 hours.

These definitions apply to a lowering task, except the word "lower" is substituted for "lift." The test protocol for lowering was essentially identical to that for lifting, and the results are reported in a similar format. It should be noted, however, that the test protocols for lifting and lowering involved using a special apparatus that returned the box to its original specified location, so that the subject *only* lifted or lowered, not both.

The subject was instructed to adjust the weight of the box, according to his or her own perceptions of effort or fatigue, by adding or removing steel shot or welding rods from a box. The box had handles and a false bottom to eliminate visual cues. Each task experiment was broken into two segments so that the initial weight of the box could be randomly varied between high versus low so that the subject approached his or her maximum acceptable weight from above as well as below. If the results met a 15% test–retest criterion, the reported result was the average of these two values. If the results did not meet this criterion, they were discarded and the test repeated at a later time.

In reporting the results, it was assumed that the gender-specific maximum acceptable weights for a particular task were normally distributed. As a consequence, the results were reported as percentages of population, stratified by gender. The Liberty Mutual tables are organized around the following percentages: 90%, 75%, 50%, 25%, and 10%.[6] The 90th percentile refers to a value of weight that 90% of individuals of that gender would consider a maximum acceptable weight (90% "acceptable"), while the 10th percentile refers to a value of weight that only 10% of individuals of that gender would find acceptable (10% "acceptable").

Important Caveats

Snook and Ciriello have identified several important caveats that should be remembered when using the Liberty Mutual tables.[6]

1. The data for each experimental situation were assumed to be normally distributed when the maximum acceptable weights and forces acceptable to 10%, 25%, 50%, 75%, and 90% of the industrial population were determined.
2. Not all values in the tables are based on experimental data. Some values were derived by assuming that the variation noted for a particular variable for one type of task would be similar to that observed for another task, e.g., the effects on lowering would be similar to that on lifting.
3. The tables for lifting, lowering, and carrying are based on boxes with handles that were handled close to the body. They recommend that the values in the tables be reduced by approximately 15% when handling boxes without handles. When handling smaller boxes with extended reaches between knee and shoulder heights, they recommend reducing the values by approximately 50%.
4. Some of the reported weights and forces exceed recommended levels of energy expenditure if performed for 8 or more hours per day. These data are italicized in the tables.
5. The data in the tables give results for individual manual materials handling tasks. When a job involves a combination of these tasks, each component should be analyzed separately, and the component with the lowest percent of capable population represents the maximum acceptable weight or force for the combined task. It should be recognized, however, that the energy expenditure for the combined task will be greater than that for the individual components.

Some recent data suggest that persons performing lifting tasks are relatively insensitive to the perception of high disc compression forces on the spine.[9] As a result, there may be some tasks in the tables that exceed recommended levels of disc compression.

Related Research

Task and Subject Variables

A variety of researchers have examined the effects of other task and subject variables using the psychophysical protocol. Most of these studies involve a small number (<10) of college students as test subjects. Some experiments used the Liberty Mutual protocol; others used the protocol described by Ayoub et al.[7] and Mital.[8] These "refinements" are summarized in Table IV.

Table IV

Miscellaneous Task Variables Evaluated Using the Psychophysical Methodology.

Task Variable(s)	Reference(s)
Zone of lift	5–8, 21–23
Distance of lift	5–8, 21–23
Frequency of lift	5–8, 21–23
Box width	5–8, 21–24
Extended work shifts	8
Combinations of lift, carry, and lower	11, 12
Angle of twist	23
Box length	23, 24
Material density	25
Location of center of gravity	25
Center of gravity relative to preferred hand	25
Sleep deprivation	26
Bag versus box	26
Fullness of bag (same weight)	26
Bag ± handles	26
Day 1 to day 5 of work week	19
Asymmetrical loads	28–30
Asymmetrical lifting	28–31
Emergency scenario	32
Handle position	33
Handle angle	33
Duration of lifting	34, 35
Overreach heights	36
Restricted vs. unrestricted shelf opening clearances	37
Experienced vs. inexperienced workers	38
Nonstandard or restricted postures	20, 39–41

Recommended Applications

Job Evaluation

The Liberty Mutual tables were developed for the purpose of evaluating work, not workers.[10] In particular, the tables are intended to help industry in the evaluation and design of manual materials handling tasks that are consistent with worker limitations and abilities.[6] The explicit goal is the control of low-back pain through reductions in initial episodes, length of disability, and recurrences.[10]

To apply the tables in the context of job evaluation, it is first necessary to specify the task variables of the job. For a lifting task, this includes the lift zone, distance of lift, box width, frequency of lift, and the presence or absence of box handles. In addition, it is necessary to measure the weight of the object to be handled, perhaps using a scale or dynamometer. Once these variables are specified, the measured weight can be compared to the data in the table to determine the percent of capable population for males and females. The procedure is similar for pulling or pushing. The required force can be measured with a dynamometer.

Consider the following example. The task is to lift a 49-cm wide box that weighs 20 kg once every minute between floor level to knuckle height for a distance of 51 cm. In Table V, excerpted from the Liberty Mutual tables, the weight of the box, 20 kg, is exactly equal to the maximum acceptable weight of lift for 75% of males, that is, 75% of males would consider this task "acceptable." By contrast, the highest maximum acceptable weight of lift reported for females is 18 kg. As a result, this task is "not acceptable" to more than 90% of females.

Table V

Excerpt from the Liberty Mutual Tables for Maximum Acceptable Weight of Lift (kg) for Males and Females.

				Floor Level to Knuckle Height One Lift Every							
Gender	Box Width (cm)	Distance of Lift (cm)	Percent Capable	5 sec	9 sec	14 sec	1 min	2 min	5 min	30 min	8 hr
			90	7	9	10	14	16	17	18	20
			75	10	13	15	20	23	25	25	30
Males	49	51	50	***14***	17	20	27	30	33	34	40
			25	***18***	***21***	25	34	38	42	43	50
			10	***21***	***25***	***29***	40	45	49	50	59
			90	***6***	7	8	9	10	10	11	15
			75	***7***	9	9	11	12	12	14	18
Females	49	51	50	***9***	10	11	13	15	15	16	22
			25	***10***	***12***	13	16	17	17	19	26
			10	***11***	***14***	15	18	19	20	22	30

Italicized values exceed 8-hour physiological criteria (energy expenditure).

Job Design

To apply the tables in the context of job design, the process is essentially identical. All task-specific parameters must be identified, except the required weight or force (that is what you are determining). You select a desired percent of capable of population, noting gender effects, then identify the maximum acceptable weight or force that corresponds to that desired percent. This is the value recommended for job design.

As an example, suppose you wish to design a lifting task that requires a 49-cm wide box that must be lifted 51 cm once per minute within the floor-to-knuckle zone. You desire to design this job to accommodate 75% of females. According to the data in Table V, you would recommend that the box weigh no more than 11 kg. This weight would be acceptable to 75% of females and over 90% of males.

Multiple task analysis, consisting of lifting, carrying, and lowering, has also been investigated for the Liberty Mutual data.[11] In this circumstance, it was observed that the maximum acceptable weight for the multiple task was less than that for only the carrying task when performed separately, but not significantly different from the lifting or lowering maximum acceptable weights when performed separately. For this type of a multiple task, the maximum acceptable weight for the task should be the lowest maximum acceptable weight of the lifting or lowering task as if it were performed separately. One should be careful, however, because the energy expenditure for the multiple task is probably underestimated when compared to performing the tasks separately. Similar results were reported by Jiang et al.[12]

Validation

Content Validity

The concept of content validity, also called face validity, addresses whether the content of the test is identical or highly similar to the content of the job. This is one of the major advantages of the psychophysical methodology, but it is important for the user to realize the limitations of the data, especially the caveats noted earlier.

It is noted that a 40-minute test protocol is used to predict an 8-hour maximum acceptable weight or force. The researchers at Liberty Mutual examined this assumption by having subjects select their maximum acceptable weight according to the usual protocol, then having them continue to work, adjusting the weight or force as desired, for a total of 4 hours.[10] No statistically significant difference was found between the values selected after 40 minutes and those selected after 4 hours. Karwowski and Yates reported similar results.[13]

Mital also examined this issue relative to the Ayoub et al. data.[14] Mital found that the test subjects' estimates of their 8-hour maximum acceptable weights of lift were significantly greater than that selected at the end of an actual 8-hour period of work (an average 35% reduction). He "corrected" for this effect in his tables for 8-hour maximum acceptable weights of lift.[8]

Criterion-Related Validity

Criterion-related validity, also called predictive validity, deals with the question of whether the results of the this type of job analysis predict risk of future injury or illness. This is generally demonstrated by the presence of a statistically significant correlation between a test "score" and a particular outcome in an appropriately conducted epidemiological study.

There are two such studies relevant to the criterion-related validity of the psychophysical methodology.

Liberty Mutual Data. In 1978, Snook, Campanelli, and Hart published an investigation of three preventive approaches to low-back injuries in industry.[15] They distributed 200 questionnaires to Liberty Mutual Loss Prevention representatives throughout the United States. These representatives were asked to complete the questionnaire for the most recent compensable back injury. If the specific act or movement associated with the injury were some form of manual handling task, a task evaluation was completed to estimate the percent of capable working population that could perform the task without overexertion, e.g., what percent of the population could perform the task without exceeding their maximum acceptable weight or force.

The investigators received 192 questionnaires, one with incomplete data. They observed that 70% of these 191 low-back injuries were associated with manual materials handling tasks. They also compared the observed number of injuries to an expected number of injuries according to whether the percent capable population was greater than or less than 75%. This analysis is summarized as follows:

	≥ 75% capable	< 75% capable
Observed	98	93
Expected*	145.9	45.1

* The expected values were derived from control data that revealed that 23.6% of jobs involve handling tasks that less than 75% of the population could perform without overexertion.

$$X^2 = 66.6;\ p < .01$$

Based on these results, the authors concluded:

1. A worker is three times more susceptible to low-back injury if he or she performs a job that less than 75% of the working population can perform without overexertion.
2. At best, the ergonomic approach could reduce low-back injuries associated with manual material handling tasks by 67% by designing the jobs so that percent capable population were 75% or greater. The remaining 33% of back injuries will occur regardless of the job demands.
3. Since only 50% of the industrial back injuries are related to manual materials-handling tasks where the percent capable population is less than 75%, the overall reduction in in low-back injuries would be 33%. This reduction would be higher if the percent capable population were raised to 90%.

Ayoub et al. Data. Ayoub and co-workers proposed the use of a severity index, called the Job Severity Index (JSI), for purposes of validation.[16] The JSI is a ratio of job demands to worker capability. Since a job may consist of multiple tasks, they defined the JSI as a time- and frequency-weighted average of the maximum weight required by each task divided by the task-specific worker capacity. Their validation studies included 101 jobs, performed by 385 males and 68 females, and involved four steps:

1. Selection of candidate jobs.
2. Analysis of candidate jobs in terms of lifting requirements and morbidity data.
3. Determination of the JSI for jobs and operators.
4. Determination of the relationship between JSI and observed morbidity.

Individual JSIs were calculated for each worker that were subsequently grouped in to four categories: $.00 \leq$ JSI $< .75$; $.75 \leq$ JSI < 1.5; $1.5 \leq$ JSI < 2.25; and JSI ≥ 2.25.

The morbidity data were classified into five groups: musculoskeletal injuries to the back; musculoskeletal injuries to other parts of the body; surface-tissue injuries due to impact; other surface-tissue injuries; and miscellaneous injuries. These data were reported as incidence rates per 100 workers per year. Data for severity (days lost) and cost were also collected.

The results revealed that the incidence of back injuries and the incidence of disabling back injuries increased substantially if the JSI was greater than or equal to 1.5. The relationships were nonlinear. The severity for disabling back injuries was increased if the JSI was greater than 2.25. The authors did not report any statistical analyses.

Another aspect of their validation involved classifying jobs according to the percent of capable population. Each job was categorized according to the percentage of the population "overstressed," that is, JSI greater than 1.5. The ranges were: $\% > 75$; $5 < \% \leq 75$, and $\% \leq 5$. They observed that the incidence of back injuries, incidence of disabling injuries, days lost per injury, and total cost increased as the percent of population "overstressed" increased. The authors did not report any statistical analyses.

Both Sets of Data. Another study that examined the predictive validity of the psychophysical methodology was published by Herrin, Jaraiedi, and Anderson.[17] These investigators performed detailed biomechanical and psychophysical evaluations on 55 industrial jobs from five major industries. The psychophysical analyses involved determining the minimum percent of capable population from the Liberty Mutual tables for each individual task (PSY.MIN) as well as an average percent of capable population when the job involved multiple tasks (PSY.AVG). Additional comparison variables included the Job Severity Index (JSI) and Lifting Strength Ratio (LSR). These investigators modified the definition of JSI to represent a frequency- and time-weighted ratio of weights lifted compared to the average task-specific lifting strength of males and females, averaged across all tasks. By contrast, the LSR represented the worst case scenario in that it was the largest single ratio identified among all the tasks.

After the jobs were characterized as described above, injury and illness data for 6912 incumbent workers were monitored for 2 years retrospectively and 1 year prospectively (> 12.6 million man-hours). Morbidity was categorized as contact incidents, musculoskeletal disorders (excluding the back), and back incidents, and expressed as incidence rates (number of incidents per 100 workers per year). Severity data were also examined (lost-time vs. no-lost-time).

The results revealed a significant negative correlation between the minimum percent capable population (PSY.MIN) and all three incidence rates, that is, the incidence rates increased as the percentage capable population decreased. A similar correlation was noted between PSY.MIN and severity. There was no correlation between the average percentage capable population (PSY.AVG) with any incidence rate or severity. The incidence rates for musculoskeletal disorders and back disorders were positively and significantly correlated with the LSR. LSR was also correlated with severity. The JSI only correlated with severity, not incidence.

The authors offered the following conclusions:

1. Overexertion injuries can be related to physical job stresses.
2. Indices representing the extremes of the job requirements (PSY.MIN and LSR) are generally more predictive of risk than indices representing averages (PSY.AVG and JSI).
3. The percentage of capable population for the most stressful aspect of the job, either isometric or psychophysical, is the simplest index of this type.

Evaluation According to Physical Assessment Criteria

Is Psychophysical Strength Testing Safe to Administer?

According to Snook, there was one compensable injury among the 119 industrial worker test subjects.[18] This single episode involved a chest wall strain associated with a high lift. It was also associated with 4 days restricted activity, but no permanent disability.

Does Psychophysical Strength Testing Give Reliable Quantitative Values?

The Liberty Mutual protocol incorporates a criterion for test–retest reliability (maximum difference of 15%). Legg and Myles reported that 34% of their data did not meet this criterion.[19] In contrast, Gallagher and coworkers reported that only 3% of tests in their study had to be repeated because the 15% test–retest criterion was violated.[20] Clearly, the maximum acceptable weights and forces are quantitative.

Is Psychophysical Strength Testing Practical?

There are two major sources of impracticality associated with this type of strength assessment: 1) it is conducted in a laboratory, and 2) the duration of testing is somewhat prolonged compared to other strength assessment methods. It is possible, however, to have the subjects use objects that are actually handled in the workplace. Equipment is not very costly.

Is Psychophysical Strength Testing Related to Specific Job Requirements (Content Validity)?

The content validity of this method of strength assessment is one of its greatest assets. One potential weakness, however, is its insensitivity to bending and twisting.

Does Psychophysical Strength Testing Predict Risk of Future Injury or Illness (Predictive Validity)?

The results of two epidemiological studies suggest that selected indices derived from the psychophysical data are predictive of risk for contact injury, musculoskeletal disorders (excluding the back), and back disorders.[15,16] These indices are correlated to the severity of these injuries. A third study demonstrated predictive value.[17] It should be noted, however, that at high frequencies, test subjects selected weights and forces that often exceeded consensus criteria for acceptable levels of energy expenditure. In addition, test subjects may also select weights and forces that exceed consensus levels of acceptable disc compression.

Summary

The psychophysical methodology, as applied to strength, has been used to determine the maximum acceptable weights and forces associated with manual materials-handling tasks for healthy adult male and female industrial workers. The results of these studies have been published in a series of tables for lifting, lowering, pushing, pulling, and carrying. The data were primarily developed for the assessment of the strength requirements of such tasks relative to the abilities of a population of healthy adult workers. As a result, a job is analyzed by comparing the required weight or force to the percent of capable population. Applied in this manner, the job analysis results correlate with observations of morbidity, especially related to the low back.

This technique was neither developed nor standardized for the purpose of worker selection. At this time, the use of psychophysical methods of strength assessment for predicting capability or future risk of injury, illness, impairment, or disability for an individual has not been validated. In the context of a preemployment evaluation, job-specific psychophysical testing might be considered for testing ability to perform critical job tasks; however, the motivation of the test subject may affect the results. For example, an individual who is highly motivated to demonstrate capability may select a “maximum acceptable weight or force” greater than what would be selected in a different context. In terms of a preplacement evaluation, the issue may be direct threat. At this time, no evidence indicates that this testing can predict risk of future injury for an individual. The assessment of human strength by psychophysical methods therefore has limited application to the assessment of individuals. As Snook and associates state, the available data should rather be used to analyze jobs.[10]

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